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Paleotemperatures of La Malinche: a palynological hypothesis

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Paleotemperatures of the last 10,000 years at 3,100 m elevation on La Malinche volcano (Mexico) were reconstructed by treating pollen analytic data by Ohngemach and Straka with numerical techniques. Pollen data from 104 modern and 97 fossil samples were analyzed in order to: (1) calibrate transfer functions linking modern pollen data to climate and vegetation data from available maps (and cross-validate the predictive model of temperature on modern data sets), and (2) reconstruct paleotemperature for the last 10,000 years from fossil pollen data. A paleotemperature curve was obtained, that ranges between 7°C in the glacial period and 12.5°C at 8,000 years BP. It matches glacial stratigraphy. Temperature is described as follows: Section S1 (from the deposit's bottom to 8,500 years BP) from 7 to 8°C. S2 from 9.0 to 11°C. S3 (around 8,000 years BP) 11.5–12.5°C. S4 from 12 to 9°C. S5 (2,700 years BP) has poor pollen concentration and estimates are unreliable. S6 from 9 to 5.5°C. S7 (around 1,550 years BP) from 6.5 to 7.5°C; S8 (ending 1,000 years BP), from 7.5 to 9.5°C and includes anthropogenic influences. S6 is given a new interpretation: open vegetation with low local pollen production and greater influence of long distance components.

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The Cordillera Neovolcánica of Central Mexico encloses valuable testimonies of Pleistocene and Holocene glaciar advances (Heine 1988). Physical environment fluctuations triggered vegetational responses that are found in the pollen record. La Malinche volcano in Central Mexico (Fig. 1) is an excellent site for paleovegetation studies but the paucity of modern climate data prevented all attempts of quantitative paleoclimate reconstructions. The problem may be circumvented by replacing climate data with information from cartography. Montane plant formations in the Puebla-Tlaxcala region (including La Malinche) have been linked to elevation and climate belts (Beaman 1962, Klink et al. 1973, Lauer 1973, Ern 1976, Lauer & Frankenberg 1978), providing the data used in this paper.

Modern environments around La Malinche are: (1) Cold Land (2,700–3,300 m), mean annual temperature 13 to 9°C, with a gradient of 1°C each 150 m change in elevation. Vegetation is (a) a climax mesophytic coniferous forest of *Abies religiosa, Cupressus lindley, Pinus ayacahuite* and *P. pseudostrobus,* found on the western slopes of high volcanoes, and (b) a heliophytic, fire resistant association of trees, shrubs and tussock-grasses with *Pinus teocote* and *P. montezumae, Alnus firmifolia, Senecio cinerarioides* (shrub), and *Epicampes macroura* (a tussock-grass). This association has largely replaced the climax forest (Ern 1976). (2) *Frozen Land* (3,300–4,400 m), mean annual temperature 9 to 5°C, with gradients of 1°C for each 175 m change in altitude up to 4,000 m and 1°C for each 200 m in altitude from 4,000 m up. Vegetation is (c) a high altitude coniferous forest of *Pinus hartwegii,* extending from 3,000 m to the tree limit, around 4,000 m, and (d) a treeless formation of tussock-grasses, 'zacatonal', with *Festuca* and *Calamagrostis,* and some perennials: *Cirsium, Gnaphalium, Lupinus* and *Senecio* among others.

Studies of modern and Quaternary palynology of La Malinche were part of the 'Mexiko Projekt' sponsored by the Deutsche Forschungsgemeinschaft and were carried out by Straka and Ohngemach (1983; 1989). Profile Tlaloc I was described in 8 sections (S1 through S8, late Pleistocene to 1,000 AD). Profile Tlaloc II refined the record for S1 through S3.

Geological testimonies of regional paleoclimate were studied by Klaus (1973) and Heine (1975, 1988). Heine (1988) correlated the 'zacatonal' pollen zones of Tlaloc I to M III 3 glacial phase (9,000 to 8,500 years BP) and M IV Holocene neoglacial advance (3,000 to 2,000 years BP).

This work is a numerical study of modern and fossil pollen data from La Malinche by Ohngemach and Straka, designed to (a) produce a predictive model of temperature cross-validated on modern data sets, (b) reconstruct paleotemperature for the last 10,000 years. It is assumed that the extant relationships between pollen frequencies and temperatures also existed in past. The results were obtained by (1) selection of modern samples similar to the fossil samples; (2) identification of the best transfer function for paleotemperature by multiple linear regression; model calibration and reconstruction of paleotemperature of Tlaloc I and II.

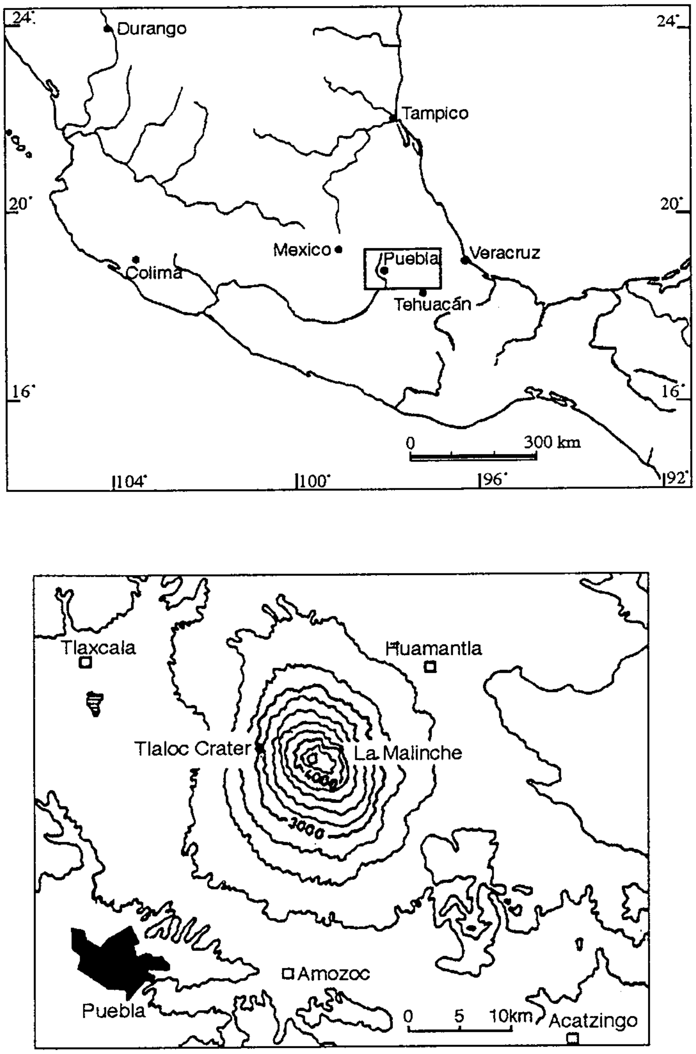

Fig. 1. A. Location of La Malinche Volcano in Central Mexico. B Detail of La Malinche Region and location of the Tlaloc Crater (From Ohngemach & Straka 1983, modified).

MATERIALS

Modern annual temperatures. Each sampling site was located within a climate belt on the map by Lauer and Frankenberg (1978). Temperatures were calculated for each sample based on the gradient at the respective elevation belt.

The modern pollen record consists of 104 surface soil samples from the Citlaltepetl, La Malinche, Popocatepetl and Nevado de Toluca volcanoes between 4,700 and 2,550 m above sea level.

The fossil pollen record consists of 49 spectra from profile I and 48 from profile II of the secondary crater Tlaloc, on the west slope of La Malinche, at 3,100 m (Fig. 1). A black gyttja level present in both profiles was dated 7,970 ± 70 ^{14}C years BP (Ohngemach & Straka 1983).

METHODS

Two related procedures requiring independent variables and one or more response variables have been used in palynological paleoclimatology: multiple linear regression (MLR), and response surface methods (RSM). MLR is easier and better known by biologists but, it treats climate as a response to pollen variables and requires the satisfaction of statistical assumptions which are often difficult to meet with pollen data (Howe & Webb 1983, Webb 1985). RSM on 2 or more climate variables treat pollen frequencies as responses and relate variables and responses in a non-linear fashion (Bartlein et al. 1986). Past climates are inferred from the response surfaces by comparing the frequencies of a selected taxon from a fossil assemblage with the modern pollen frequencies and associated climate values for the same taxon as presented on the response surface. The individual climate estimates from each pollen taxon can then be combined to arrive at a collective estimate (Bartlein et al. 1986, Prentice et al. 1991). However, climate estimates from each of the surfaces may be non-singular, making climate estimates based on one taxon impossible and requiring empirical weighing of each taxon to arrive at a collective estimate. Inferences about climate from fossil samples which lack analogues in the modern pollen record are prone to the same uncertainties as similar estimates made with multiple regression equations (MacDondald & Reid 1989).

MLR was selected for this work since Tlaloc crater is located in the middle of a rather ideal gradient where the relationships of pollen variables to temperature are close to linear. Climate data were calibrated in terms of modern pollen data to produce predictive models that, in turn, were used with fossil spectra for analyzing and modeling paleoclimate.

a) *Initial Calibration pollen sum.* – To enter this sum a pollen type should (1) occur in fossil pollen spectra of Tlaloc I and/or II, (2) occur in modern pollen spectra of sites from Cordillera Neovolcánica, (3) have a mean value of 1% or more throughout the data set or reach a maximum value of 5% or more at least once in the profiles and in the surface samples. Species of *Pinus, Alnus,* Gramineae, Compositae, *Quercus, Juniperus* + *Cupressus, Abies, Salix,* Anacardiaceae and *Arceuthobium* satisfied the above conditions. New pollen sums were calculated for both modern and fossil spectra including only these 10 types.

b) *Preliminary analogies.* – Fossil and modern samples were treated with k-means cluster analysis (Engelman 1980, Engelman & Hartigan 1985) for a coarse identification of modern analogues for the fossil samples. Up to 25% dispersion was allowed around the centroid of the respective cluster. This condition produced a major screening as only 34 out of 104 modern samples satisfied it.

c) *Calibration.* – Calibration of pollen spectra in terms of temperature was performed with MLR of all possible subsets. The first runs identified outliers to be removed from the data set. The 'best' model was selected by Mallow's Cp statistic and controlled by Squared Multiple Correlation (SMC) and SMC adjusted for the number of predictors. In includes 17 samples from La Malinche and 3 from Nevado de Toluca.

d) *Cross validation.* – Seven samples selected at random were used as controls and their temperatures were predicted by the remaining 13.

e) *Paleotemperature hindcasting.* – Fossil samples were fed to the calibrated model and paleotemperatures were hindcasted.

RESULTS

Models for temperature reconstruction. Observed temperatures for modern samples range from 5.7°C to 12.7°C, and calibration was performed with 9 terms: *Pinus, Alnus, Quercus, Abies, Salix, Arceuthobium,* Gramineae, Compositae and Anacardiaceae (Table 1).

A final run generated 81 models including 1 to 9 pollen variables. R^2 and Adjusted R^2 values were above 0.9 in models with 3 variables or more. Bias, as measured by Mallow's Cp index, was lowest in a 5-variables model. This one was identified as the 'best' predictive model, including

Table I. *Summary statistics for each variable in the models.*

Variables	Mean	Std.dev.	Smallest	Largest
Pinus	51.41	15.16	32.14	81.31
Alnus	4.64	3.83	1.37	17.30
Gramineae	14.07	18.18	1.12	49.95
Quercus	6.30	7.79	2.26	38.83
Compositae	6.56	2.36	3.55	13.36
Abies	6.22	6.56	0.20	19.46
Salix	0.47	1.20	0.00	5.49
Anacardiaceae	1.58	1.10	0.00	3.98
Arceuthobium	3.16	4.80	0.00	14.74
Temperature	8.09	1.81	5.75	11.66

Pinus, Alnus, Gramineae, *Abies* and Anacardiaceae, as follows:

$$\text{Temperature} = \underset{(.852)}{9.327} + \underset{(.009)}{0.015}\ Pinus + \underset{(.034)}{0.109}\ Alnus$$

$$- \underset{(.010)}{0.054}\ \text{Gramineae} - \underset{(.020)}{0.096}\ \text{Abies} - \underset{(.084)}{0.744}\ \text{Anacardiaceae}$$

Additional statistics are: Mallow's Cp = 4.20; $R^2 = 0.97$; r = 0.99; Adjusted $R^2 = 0.96$; Standard error of estimates = 0.34. (standard deviations are in brackets)

Cross validation. Seven modern samples were selected at random and given 0 weight in the model. The temperatures of these 7 samples were predicted by the ones remaining in the model. Results are shown in Fig. 2 (asterisks).

Paleotemperature was reconstructed by feeding the above model with fossil pollen data from profiles Tlaloc I and II. Results are shown in Figs. 3 and 4.

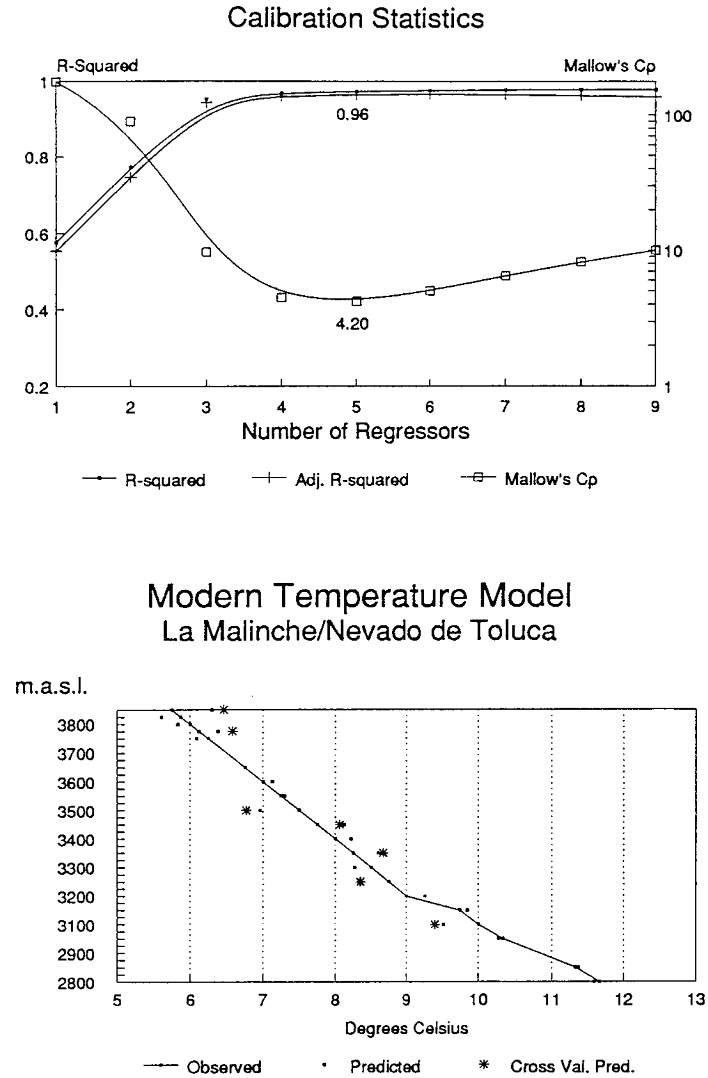

Fig. 2. The predictive model. Above: Statistics of the models. The one with 5 regressors was selected because of its low bias and high R^2 value. Below: Cross validation and predictions. Boxes are observed values, crosses are predicted values and asterisks are values obtained by cross validation, i.e., values predicted by the model for samples randomly excluded of the model.

DISCUSSION

The following discussion is arranged according to the stratigraphic sections proposed by Ohngemach and Straka (1983).

Section 1 (Tlaloc I from 284 to 256 cm; Tlaloc II from 300 to 204 cm). Mean temperature between 6.5 and 8°C. The climate was probably more humid and cooler than today. From the bottom of both profiles up to 8,500 years Before Present (years BP). It has been correlated to Moraine M III 3. 'Zacatonales' period.

Section 2 (Tlaloc 1 from 252 to 227 cm; Tlaloc II from 203 to 182 cm). Temperature rise from 9°C to 11°C. *Pinus hartwegii* (identified by correlation with pollen of its frequent parasite *Arceuthobium cryptopodium*), related to the modern vegetation of the lower 'frozen land'. *Alnus and Quercus* are present but *Picea* vanishes at the end of the brown and sandy gyttja.

Section 3 (Tlaloc I from 223 to 189 cm; Tlaloc II from 182 to 170 cm). Temperature between 11.5 and 12.5°C. Black gyttja (7,970 ± 70 years BP), containing *Alnus,* probably *A. firmifolia,* found today between 2,800 and 3,200 m with *Abies religiosa* and *Pinus montezumae,* in the upper 'cold land'. Ohngemach and Straka (1983) do not decide if this pollen assemblage reflects a successional adjustment or a rapid expansion of *Alnus* following forest fires. However, Ohngemach (1977) points out a rise of *Alnus* immediately after *Picea* vanishes in Jalapasquillo (2,400 m). Since the sediment type changes from a brown, sandy gyttja to a black gyttja and no fire indicators are mentioned, the period is interpreted as a successional stage.

Section 4 (Tlaloc I from 185 to 150 cm). Temperature drops from 12°C down to 9°C. *Pinus hartwegii* epoch.

Section 5 (Tlaloc I from 150 to 90 cm). Pumice sediments, poor in pollen, 2,670 ± 70 years BP (Heine 1988). Temperature reconstruction is unreliable due to low pollen counts.

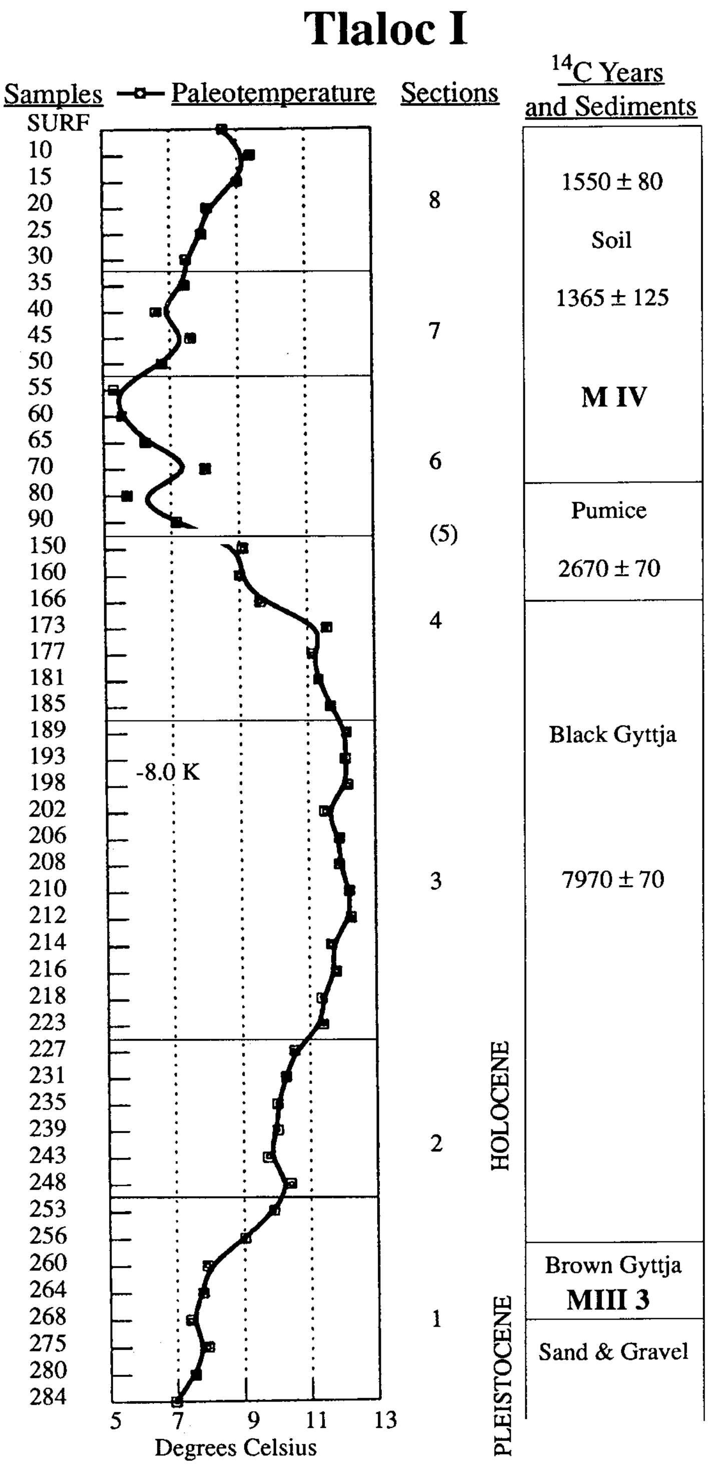

Fig. 3. Paleotemperature reconstruction for Tlaloc I, by sections. S1 (last Pleistocene glacial advance, M III 3) frozen land, zacatonal. S2, frozen to cold land, *Pinus hartwegii* forest. S3, warmer cold land with *Alnus* forest. S4, cold to frozen, *Pinus hartwegii* forest. S5 did not support temperature reconstruction. S6, frozen, Holocene glacial advance (M IV, 2,000 years BP), zacatonal. S7, frozen, forest advance (*Pinus* and *Abies*). S8, cold land, the current *Pinus* mixed forest in the crater. Agriculture of maize in the region and probably around the crater (Ohngemach & Straka 1983). On the right side, the sections as presented by Straka and Ohnegemach (1989), ^{14}C dates and sediments with M IV and M III 3.

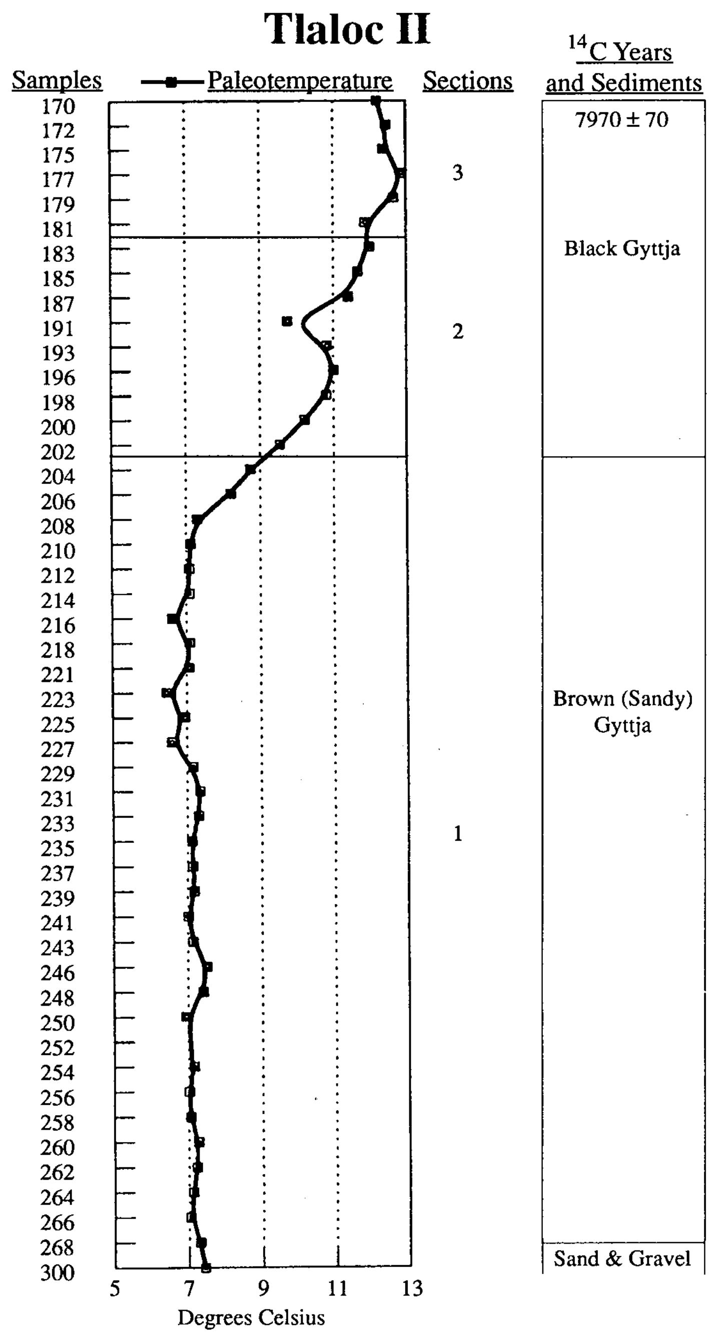

Fig. 4. Paleotemperature reconstruction for Tlaloc II, by sections. S1, last Pleistocene glacial advance, frozen, zacatonal. S2, frozen to cold, *Pinus hartwegii* forest. S3, warmer cold land with *Alnus* forest. Black gyttja level is 7,970 ± 70 ^{14}C years BP (KI-745). This date is used in Profile Tlaloc I by correlation of the black gyttja level (Ohngemach & Straka 1983).

Section 6 (Tlaloc I from 90 to 55 cm). Temperature drop from 9°C down to 5.5°C. Heine (1988) correlates it with Moraine IV. S6 might be interpreted as one of grasses, herbs and bushes related to 'zacatonal' communities. The community of *Pinus, Alnus, Abies* and *Quercus* may have been located at a lower elevation. The values recorded for *Arceuthobium* in S6 do not differ from the ones of 'zacatonal'. Future research should test this hypothesis with pollen concentration techniques.

Section 7 (Tlaloc I from 50 to 35 cm). Temperature from 6.5 to 7.5°C. *Pinus* and *Abies religiosa.* Heine (1988) places it between the end of M IV and the end of pumice sediments, around 1,550 years BP. S7 reflects an advance of today's 'climax' forest for the 2,700–3,200 m belt.

Section 8 (Tlaloc I 30 to 10 cm). Mixed *Pinus* forest. Temperature rises from 7.5 to 9.5°C while modern vegetation is established. It is 'impact' rather than low temperature and should be interpreted as a quick expansion of Compositae and other non-arboreal taxa resulted from forest clearance. NAP percentage rises from 37.4 at 10 cm depth to 51.5 in the surface sample. Ending 1,000 years BP, S8 does not include evidence of the 'Little Ice Age'.

CONCLUSIONS

1) The problem posed by the paucity of standard climate data in Central Mexico was solved by extracting data from cartography produced by the Mexiko Projekt.
2) Paleotemperatures, as reconstructed for Tlaloc I, support the correlation of glacial advances M III 3 and M IV suggested by Heine (1988). Late pleistocene temperatures were 1 or 2°C lower than those current at 3,100 m elevation. Comparable values were found in the Pleistocene-Holocene transition (256 cm) and before M IV (160 and 150 cm). The temperatures reconstructed for S6 seem to be exaggeratedly low in relation with available geological evidence (see Heine 1988). Ohngemach and Straka (1983) and Straka and Ohngemach (1989) interpret vegetation as an open mixed forest of *Pinus*, with low proportions of *Alnus* and *Abies* and high values of non-arboreal pollen. This is not consistent with their description of the 'semihumid mixed pine forest' (1983: 52). *Abies* (0–6%), *Quercus* (1.8–10%), *Alnus* (1.5–18.4%) and Gramineae (1–22.5%) are out of range in S6. *Juniperus/ Cupressus* that should range from 0.6 to 31.6% of the arboreal pollen was not found in S6.
3) The new interpretation given to S6 and S7 must be considered as an alternative hypothesis until samples are tested for pollen concentration and more ^{14}C dates are available for the sediments between 170 and 40 cm.

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